Tidal Atmospheric Loading and VLBI

Anastasiia Girdiuk, Michael Schindelegger, Johannes Böhm

Abstract This study is dedicated to the influence of diurnal atmosphere-ocean dynamics on Earth rotation and loading effects as observed by Very Long Baseline Interferometry (VLBI). In the first part, we investigate loading signals caused by atmospheric tides and the associated mass variations in the ocean. Different models are compared by means of baseline length repeatability; furthermore, consistent corrections for the atmosphere and the ocean are discussed. We also show VLBI results for two gravitational ocean tide models (FES2004 and FES2012), where the latter benefits from a much finer horizontal resolution and an improved description of hydrodynamic processes. As a result of the comparisons, the effect of changing loading is insignificant with respect to baseline length repeatability. The second part focuses on the Earth rotation variations associated with atmospheric tides, comprising small but non-negligible oscillations on the order of 10 μas. Here, we compare tidally analyzed VLBI observations against estimates from different providers of numerical weather models. In summary, changing atmospheric and ocean models in VLBI analysis does not affect the tidal terms analysis. For example, the principal atmospheric diurnal radiational S_1 tide shows a small variability for applied loads.

Keywords Geodetic VLBI analysis, tidal terms analysis, VLBI reduction, atmospheric loading, ocean loading

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1 Introduction

Tidal atmospheric loading provides a small contribution to station coordinate changes, but it should not be neglected due to its periodic behavior. Diurnal S_1 and semi-diurnal S_2 present periodic signals of the tidal atmospheric loading in the routine VLBI analysis as recommended by the IERS Conventions [8]. At the same time, the Earth's crust is affected by the irregular atmospheric non-tidal loading which is calculated based on atmospheric pressure fields as provided by meteorological models. Although this contribution to station coordinate changes is not recommended by the IERS Conventions, it causes large ground surface deviations and is thus usually corrected for in VLBI solutions. In the following we assess the impact of atmospheric tidal and non-tidal loadings as well as ocean tidal loading on baseline length repeatability (Section 3) and on tidal terms in Earth rotation parameters (Section 3.1).

2 Data

Geodetic 24-hour VLBI sessions with at least five antennas in the time span from May 1995 to May 2015 are processed by using the Vienna VLBI Software (VieVS) [7] as follows:

1. Outlier detection of observed residuals;
2. Celestial pole offset estimation to get *a priori* daily Earth Orientation Parameter (EOP) values based on the daily finals EOP time series [8];
3. Generation of long hourly Earth Rotation Parameters (ERP) time series making use of the *a priori* EOP model as described above;

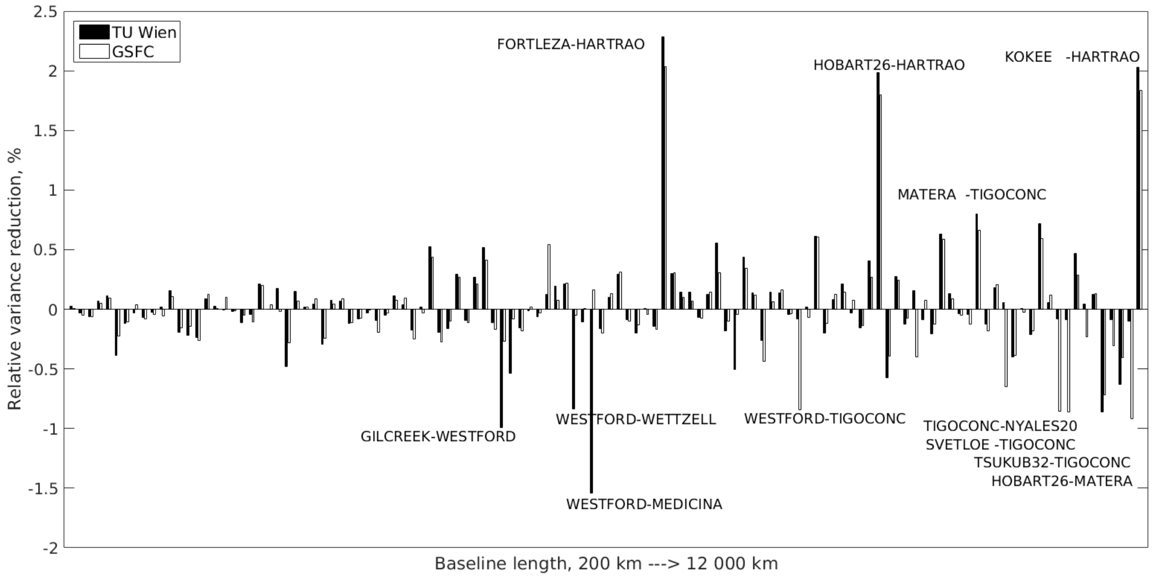

Fig. 1 Relative variance reduction for VLBI baseline length repeatabilities when using the models by TU Wien and GSFC w.r.t. not correcting for atmospheric tidal loading.

4. Estimation of baseline length repeatability in a separate run. The station coordinates are fixed to the realization by [3] in the other solutions.

A priori models, methods, and constraints are widely used and are described in detail in [3] and [13]. Usually, a global solution, which accumulates normal equations of all sessions available, is carried out for the determination of tidal terms in Earth rotation parameters. In spite of the extensive application of the global solution the single session time series approach is employed in this study and provides the hourly ERP values (max. 25 points per session) derived by inverting each VLBI session separately in VieVS.

Table 1 Description of the atmospheric and ocean models.

Model	Weather Model	Land-sea Mask
TU Wien	Tidal: European Centre for Medium-Range Weather Forecasts (ECMWF) delayed cut-off stream (DCDA) every 3 h Non-tidal: ECMWF 6h with 1° resolution	determined from Earth TOPOgraphic terrain model ETOPO5 1° resolution
GSFC	National Center for Environmental Prediction (NCEP) Reanalysis 6 h with 2.5° resolution	from Finite Element Solution FES99 0.25° resolution
Model	**Weather Model**	**Uniform Grid**
FES2004	S_1: from R. Ray, operational (op.) ECMWF 6 h	1/8°
FES2012	S_1: op. ECMWF DCDA 3 h anal.	1/16°

3 Analysis

Tidal atmospheric loading as provided by TU Wien (Vienna University of Technology) [15] and Goddard Space Flight Center (GSFC) models [10] are compared in this study. A description of these models is presented in Table 1. The main differences are in the calculation methods, the weather models, and the land-sea masks. The calculation of atmospheric pressure fields is divided into two parts [11] for both models: the tidal part as recommended by the IERS Conventions and the non-tidal part, which is not accounted for in the IERS Conventions. The underlying weather models have different providers and grid resolutions: the TU Wien model uses a finer resolution. The implemented land-sea mask has a better resolution in the case of the GSFC model. However, both are not consistent with the uniform grid of the two ocean models.

Changes in loads are analyzed by means of relative variance reduction expressed as percentage. The variance reduction is calculated for the baseline length repeatability, and, thus, the relative variance is the differ-

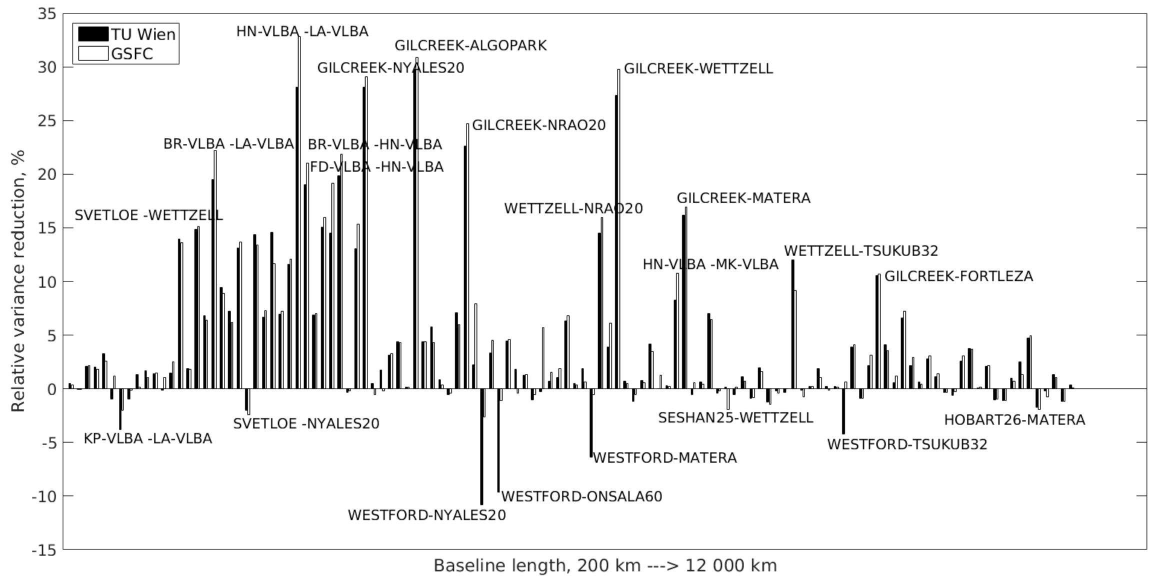

Fig. 2 Relative variance reduction for VLBI baseline length repeatabilities when using the models by TU Wien and GSFC w.r.t. not correcting for atmospheric non-tidal loading.

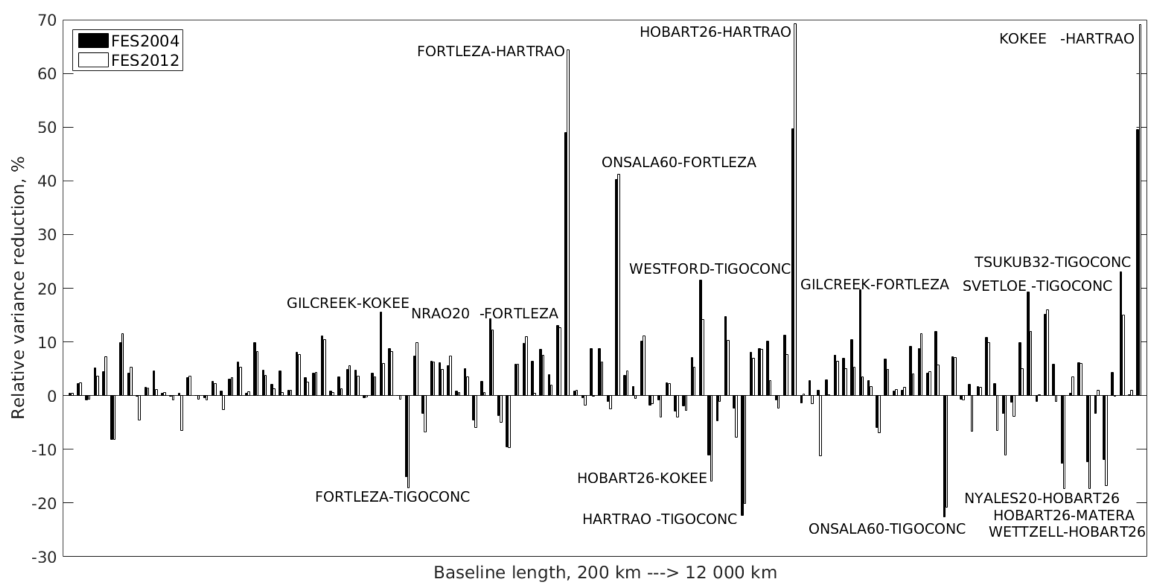

Fig. 3 Relative variance reduction for VLBI baseline length repeatabilities when using the models FES2004 and FES2012 w.r.t. not correcting for tidal ocean loading.

ence between the squared repeatabilitites of the same baseline normalized by a reference one. For this reason the station coordinates are calculated in a separate run, and several solutions are obtained: two solutions with respect to both TU Wien and GSFC (tidal and non-tidal loadings included) and two solutions (for each provider) disregarding tidal and (two solutions as well) non-tidal loading. As the major condition, the baselines observed in at least 100 sessions are assembled, and, also, the tidal and non-tidal loadings are available from both models during these sessions. In this setup some baselines had to be excluded in the comparison because of missing loading data.

Figure 1 shows a comparison of the atmospheric tidal loading and Figure 2 of the atmospheric non-tidal loading, where positive values represent improvements in baseline length repeatability with the corrections applied. The scattering of the relative variance reduction is smaller in the case of atmospheric tidal loading (Figure 1) than for atmospheric non-tidal loading (Figure 2). Therefore, the non-tidal part of atmospheric loading should not be neglected but taken into account as well. This is still not recommended by the IERS Conventions due to having no agreement on adopted models of non-tidal displacement. However, the statistical tests performed in this study prove that the models by TU Wien and GSFC do not have statistically significant discrepancies.

Additionally, the large ocean tidal loading influence comparably to atmosphere in station coordinate changes is tested between two models listed in Table 1: FES2004 and FES2012. In the case of ocean loading calculation the underlying weather model has a better agreement with the weather model used to calculate atmospheric corrections as provided by TU Wien; nevertheless, the uniform grid is improved for FES2012 and disagrees with both atmospheric models. The station displacements were calculated by M. S. Bos and H.-G. Scherneck (Ocean tide loading provider [1]) for FES2004 and by Leonid Petrov (International Mass Loading Service [9]) for FES2012. The relative variance reduction is used similar to the comparison of atmospheric loadings. The reference solution does not account for ocean loading at all and is compared with solutions in Figure 3 where FES2004 or FES2012 are applied. In the same way, the positive numbers depict baseline repeatability improvement when introducing the FES2004 or FES2012 models. Also, several baselines show degradation of the model performance and demand further investigation as well as identical behavior of atmospheric models. Again, there is no evidence that one ocean model has a statistically better value.

3.1 Tidal Terms Analysis

Hourly original ERP time series of polar motion and length-of-day (converted from Universal Time difference (dUT1)) are processed by means of a single session time series approach. Least-squares adjustment is employed for processing of the ERP time series with standard deviations as provided by VieVS introducing a stochastic model as well.

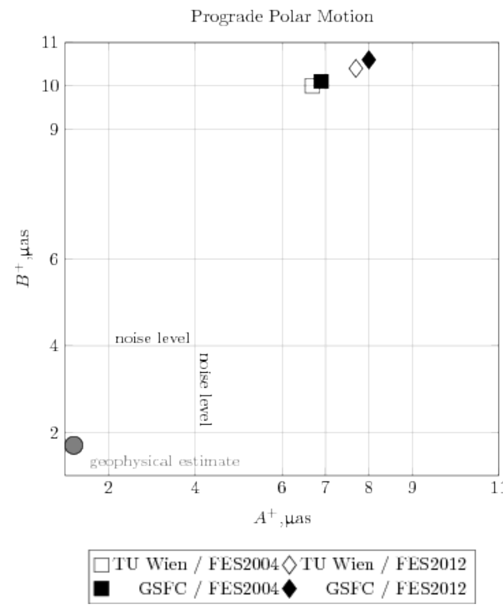

Fig. 4 Tidal terms analysis for prograde polar motion at S1.

Diurnal and semi-diurnal prograde A_j^+, B_j^+ and retrograde A_j^-, B_j^- coefficients are estimated in a standard harmonic model, e.g., for pole coordinates at epochs t_i:

$$\begin{aligned} x_p &= \sum_{j=1}^{n} \; (-A_j^+ - A_j^-)\cos\alpha_j + (B_j^+ - B_j^-)\sin\alpha_j, \\ y_p &= \sum_{j=1}^{n} \; (B_j^+ + B_j^-)\cos\alpha_j + (A_j^+ - A_j^-)\sin\alpha_j, \end{aligned} \tag{1}$$

where $\alpha_j = \alpha_j(t_i)$ are the angular (fundamental) arguments [14]. All in all 70 tides (neglecting gravitational S_1, i.e., only radiational S_1 are estimated) as published in the IERS Conventions plus six zero tides, where no excitation signals are expected, are estimated based on a high-frequency (HF) ocean model. The HF ocean model from the IERS Conventions is applied as a priori in the single session VieVS processing and consistent with the FES2004 ocean model. In case of FES2012 the a priori HF ocean model (26 tides) has been calculated by Matthias Madzak (PhD thesis [6]) and applied consistently with FES2012 ocean tidal loading.

Tidal terms analyses were performed for every solution differing in atmospheric and ocean loading corrections to investigate inconsistencies (about 10 µas) with geophysical estimates (about 2 µas) obtained by M. Schindelegger et al. [12]. For this reason we focus on the principal diurnal atmospheric tide S_1 shown in Figure 4. Zero tides are introduced in the model additionally and used to mark noise levels in the obtained time series. The differences between the S_1 estimates in Figure 4 with respect to the underlying atmospheric and ocean models for station corrections are on the noise level of the obtained time series and seem to be insignificant, similar to the comparison of these models by means of baseline repeatability. Unfortunately, the efforts undertaken in this study focusing on the changes in different loads do not solve the problem of an approximately 10 µas discrepancy between the geophysical estimate and the VLBI derived estimates as obtained in this work (see Figure 4).

4 Conclusions

The tidal atmospheric loading is applied in VLBI reductions as a small correction for station coordinates; however, the atmospheric non-tidal loading is still not accounted for in the IERS Conventions and improves baseline length repeatability significantly (3% for tidal loading vs. up to 35% for non-tidal loading). Atmospheric corrections for station positions were varied between two models as provided by TU Wien and GSFC, with the two models having a very good agreement. Additionally, ocean tidal loading was tested between the models FES2004 and FES2012 because of its large contribution to station coordinate changes (improving the baseline length repeatability by up to 70%). The discrepancies when using these models are not significant, similar to the atmospheric models. In the same way, tidal terms analysis does not reveal any differences between solutions obtained in this study, where the loads are replaced by different providers. Thus, this topic requires further investigation because of the big discrepancy with geophysical estimates.

Acknowledgements

Financial support for this study was made available by the IAG travel grant and the Austrian Science Fund under project ASPIRE (I1479).

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